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ORIGINAL PAPER

Separating in-shell pistachio nuts from kernels using impact vibration analysis

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Abstract A sorting system has been developed for the separation of small in-shell pistachio nuts from kernels without shells on the basis of vibrations generated when moving samples strike a steel plate. Impacts between the steel plate and the hard shells, as measured using an accelerometer attached to the bottom of the plate, produce higher frequency signals than impacts between the plate and the kernels. Signal amplitudes, on the other hand, were highly variable and by themselves were not useful for the separation of samples. An algorithm was developed using both amplitude and frequency information to classify the signals. The algorithm activated an air nozzle to divert in-shell nuts away from the kernel stream. A prototype sorter was tested at throughput rates of 0.33, 10, 20, and 40 nuts per second using a mix of 10% in-shell and 90% kernels. At the lowest throughput rate, classification accuracies were 96% for in-shell nuts and 99% for kernels. For throughput rates between 10 and 40 nuts/s, correct classification ranged from 84 to 90% for in-shell nuts. For kernels, accuracy was 95% at 10 and 20 nuts/s and 89% at 40 nuts/s.

Keywords Sorting · Impact vibration · Kernels · In-shell · Pistachios

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Introduction

For certain defects, the pistachio industry has adopted high quality standards. For example, each ton of shelled kernels is allowed no more than two pieces of shell; a level not currently possible using automated sorters. Consequently, after machine sorting the product must be manually inspected, which is labor intensive, costly, often inconsistent, and potentially un-sanitary. Other defects and foreign material present similar detection challenges. Some, such as sticks, are removed with automated color sorters. Improving the performance of existing sorters would clearly benefit the industry as well as the consumer. Alternatively, new approaches to sorting for certain defects or contaminants as a replacement for expensive existing equipment would also be a benefit. In this spirit, efforts are under way to design and construct economical sorting solutions for specific tasks, rather than applying expensive one size fits all technology. Haff and Jackson (in press) reported a low cost method using optical sensors for sorting in-shell pistachio nuts from kernels at a small fraction of the current cost. This work reports a method for sorting this same pistachio stream using impact vibration analysis with comparable price and accuracy to the optical methods.

In most cases, the pistachio processing stream is separated between in-shell (nuts still in their shells) and kernels (no shells). Each stream undergoes both hands sorting and sorting by machines, including color and near infrared (NIR). Monochromatic sorters measuring visible wavelengths are most common, but more recently dual-band NIR sensors are gaining acceptance. In-shell nuts can be correctly classified as much as 98.6% of the time with 99.9% of kernels correctly classified with dual band NIR sensors [1]. While this level of accuracy seems impressive, it still falls short of the requirement of no more than two shell pieces in a ton of kernels, and even after repeated sorting kernel processing streams will generally require hand sorting. Nuts with heavily stained shells of approximately the same size as an average kernel, known as small in-shell, are generally the problem as they tend to defeat both the color sorters and sizing equipment. The method reported here does not rely on color for the detection of the shells and should therefore be ideal for solving the small in-shell problem.

Beyond the use of NIR and color sorters, only a limited amount of research to develop non-destructive sorting devices for pistachio nuts has been reported. Ghazanfari et al. [2, 3] utilized Fourier descriptors and gray level histogram features of two-dimensional images to classify pistachio nuts into one of three USDA size grades, as well as identifying those having closed shells. In-shell pistachios can thus be classified using gray scale images, regardless of whether they have open or closed shells. However, processing two-dimensional images is computationally expensive and not readily implemented into a real time sorting system requiring a high throughput. Furthermore, unless the axial rotation of the nut was mechanically constrained, three images would be required to cover the entire surface. A sorting system based on two-dimensional imaging is therefore considered uneconomical.

There has been some research reported describing the use of acoustic signals to classify food products. Pearson [4] developed an economical and rapid system for separating pistachio nuts with closed from open shell based on the acoustic emission. Several researchers have found an inverse correlation between fruit firmness and resonant frequency [5, 6]. Most of the acoustical systems developed thus far involve tapping the food with a plunger, recording the resulting sound, then digitally processing the microphone signal to extract dominant frequency bands or other signal features correlated with firmness. Younce and Davis [7] developed such a system to measure firmness of cherries using impact acoustics. Sugiyama et al. [8] developed an acoustical firmness tester for melons that measured sound transmission velocity. This technique eliminated some error caused by size and shape variations in the fruits.

Very little research is reported using impact vibration analysis for classifying food products. One exception is a system that has been developed and implemented to separate walnut shell fragments from nut meats based on the vibration induced while impacting a steel plate [9]. This system utilized signal duration and peak amplitude of band pass filtered accelerometer signals.

Preliminary experiments for distinguishing in-shell pistachio nuts from kernels were unsuccessful using the acoustic emission system of Pearson [4] or a vibration signal processing scheme of Delacy et al. [9].

The objective of this research was to establish the feasibility of using impact vibration analysis as a basis for sorting in-shell pistachio nuts from kernels in real time at commercial processing plant speeds. A prototype sorter was to be constructed and tested, and results compared with other methods previously reported. The sorter should be tested for accuracy depending on the throughput rate of the product and compared to existing commercially available equipment.

Materials and methods

A prototype sorting and data collection system was constructed to record the vibration on a stainless steel plate due to an impacting nut. The prototype was adapted to sort nuts in real time after a signal processing and classification algorithm was implemented. A schematic of the system is shown in Fig. 1.

Samples of pistachio kernels and in-shell nuts were collected from the hand inspection stations at a pistachio processing plant immediately prior to shipping. These samples had already passed through color sorters, pneumatic separators, and sizing equipment without rejection, implying that the in-shell nuts were, in general, heavily stained and comparable in size to the kernels. Kernel weights averaged 583 mg (σ = 110 mg), while the in-shell nuts averaged 525 mg (σ = 162 mg).

A vibratory feeder (FT00, FMC Corp. Homer City, PA) forced the nuts in single file from a vibration feeder onto an 80 cm long slide made from stainless steel sheet metal. The slide, inclined at 60° above the horizontal, terminated above a steel plate onto which the nuts impacted. The steel plate of dimensions 5.08 cm by 5.08 cm by 0.1524 cm

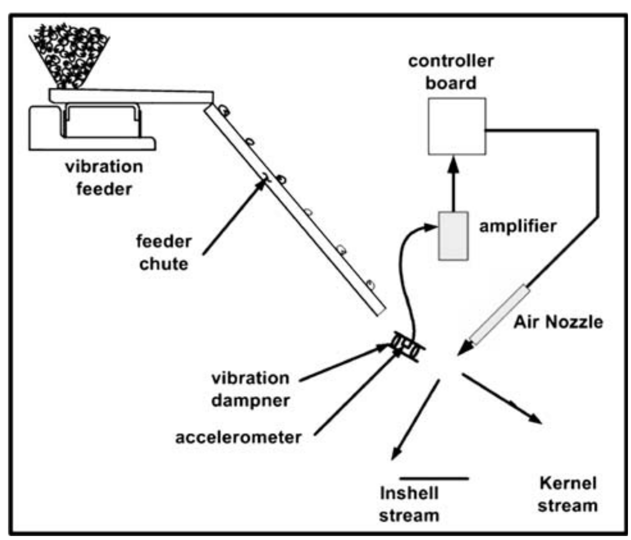

Fig. 1 Schematic of prototype sorting apparatus

(2″ by 2″ by 0.06″) was mounted on four rubber vibration dampeners (5822K8, McMaster Carr, Elmhurst, IL). The thickness of the steel plate was selected to maximize the signal attenuated from the impact without saturating the accelerometer. The dampeners served to isolate the plate from external vibrations, such as from the feeder, while increasing the elasticity of impact and duration of contact between the nut and the plate. The impact was hence somewhat cushioned, resulting in increased feature contrast between kernels and in-shell nuts. An accelerometer (9001A, Vibra-Metrics, Princeton Junction, NJ) was mounted below the plate using adhesive recommended by the manufacturer of the accelerometer (Depend 20251 Kit, Loctite, Rocky Hill, CT). A dual power supply/amplifier unit (P5000, Vibra-Metrics, Princeton Junction, NJ) provided accelerometer power as well as a ten-fold signal amplification. The output signal, which approximately ranged between ±1 V, was offset by 3 V using an op-amp circuit so that the entire signal could be captured using a 0–5 V analog-to-digital (A/D) converter.

The A/D conversion and signal processing was conducted on a high-speed controller board (RA, Tern Corp. Davis, CA). The rate of A/D conversion was 250 KHz at 12-bit resolution between 0 and 5 volts. Storage of the signal was triggered when the slope of the amplified accelerometer signal exceeded 0.1 volts between four A/D samples. After triggering, 250 A/D samples were collected and either saved onto a compact flash card on the controller board or processed as discussed below.

A decision algorithm for classifying the vibration impact signals as derived from either kernels or small in-shell nuts was developed as follows. First, the raw accelerometer signals from 100 kernels and 100 in-shell nuts (the training set of samples) were saved to a compact flash card for off-line analysis. Examples of these signals are shown in Fig. 2. Note that the higher maximum signal amplitude for the in-shell nut of Fig. 2 is merely coincidental. In fact, mean centered maximum signal amplitudes ranged from 400 to 1200 A/D counts with kernels having slightly higher mean maximum amplitude (755) than in-shell nuts (690). The high variability in signal amplitudes was addressed by dividing each point in the mean centered signal by the maximum value in each signal. This normalization gave each signal a range from –1 to 1. Next, the gradient of the signals were computed using a gap of ±1 data point as shown in Eq. 1:

$$Gradient(x) = abs(Nsignal(x-1) - Nsignal(x+1)), \tag{1}$$

where *Gradient(x)* is the absolute value of the gradient at sample number x computed from the normalized signal (*Nsignal*) at points $x{-}1$ and $x+1$. Finally, a 50 bin cumulative histogram was computed for all gradient values, giving a mapping that counts the cumulative number of observations in all of the bins up to the specified bin. The maximum histogram gradient was 0.5 so each bin value represented a 0.01 step in gradient value. All gradient values greater than 0.5 were clamped to 0.5 in order to reduce the number of histogram bins. Gradient values greater than 0.5 only occurred at one instance in the 100 in-shell nuts analyzed, and did not occur in any of the 100 kernels.

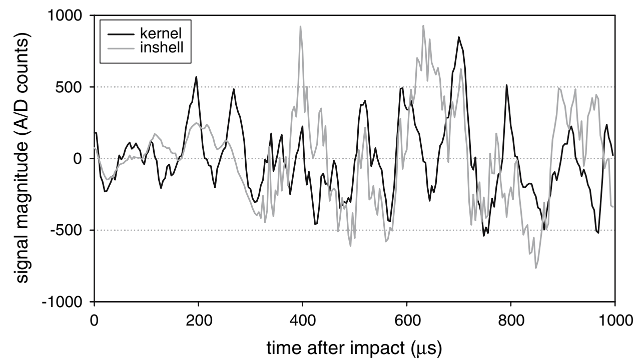

Fig. 2 Example mean centered accelerometer signals from a pistachio kernel and an in-shell nut

Average cumulative histograms for in-shell nuts and kernels are shown in Fig. 3. Kernels show a higher percentage of low gradients (less than 0.2) while in-shell nuts have higher counts of gradient values between 0.2 and 0.4.

An iterative stepwise discriminant analysis routine was used to determine the best subset of the cumulative histogram bins for use as features for deriving a decision boundary between kernels and in-shell nuts in the feature space. All data points were used in the selection of features and the computation of group means and covariances. The resulting decision algorithm thus consisted of the

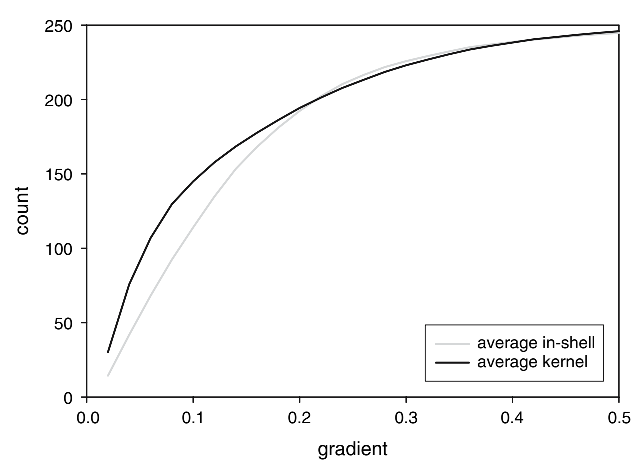

Fig. 3 Average cumulative histograms of gradient values for pistachio kernels and in-shell nuts

discriminant function (decision boundary) in the feature space into which the gradients extracted from each signal to be classified were input.

After signal processing, feature extraction, and programming of the decision algorithm onto the controller board, the performance of the discriminant function was validated by processing a separate set of 1,000 samples with the sorting device. This validation set of samples was made up of 10% in-shell nuts and 90% kernels. Samples classified as in-shell were diverted to a separate stream through the activation of an air valve (35A–AAA–DDBA–1BA, Mac Valves, Inc., Wixom, Mich.). The error in the sorting experiments can be divided into two sources: the algorithm itself and the routing of the samples into the intended stream. The computation speed of the controller board is such that throughput rate is not an issue in the classification stage. However, high throughput rates produce errors in the diversion process when more than just the intended sample is diverted due to close packing of the nuts. Reducing the duration of the air blast to compensate for high throughput requires precise timing and can result in the sample not being diverted as intended. To determine the effect of throughput on accuracy, the validation samples were processed at rates of 10, 20 and 40 nuts per second and the subsequent sorting accuracies were tabulated. Rates were adjusted by adjusting the vibration frequency on the feeder to have a desired rate based on a previous 2,000 nut count sample used for calibrating the feeder. For each throughput rate, the experiment was replicated 10 times with the same validation samples. The average and standard deviation of the sorting accuracies were computed.

In addition, a separate trial was conducted in which 100 in-shell nuts and 100 kernels were processed at a rate of approximately one every 3 s. This allowed the accuracy of the decision algorithm and the physical diversion process to be determined separately. This experiment was also repeated 10 times and the average and standard deviations computed. Algorithm error and handling error were thus determined, compared, and discussed.

Results and discussion

The stepwise discriminant procedure selected the cumulative histogram features at bins representing gradients of 0.04 and 0.24 as giving the best separation in feature space. Discriminant functions comprising 3 or more features did not improve classification accuracy over two features. Figure 4 confirms that kernels have higher gradient counts of magnitude less than 0.04 and in-shell nuts have higher gradient counts at of magnitude less than 0.24. This was to be expected as the vibration signal induced by kernels is much smoother than that from in-shell nuts. Smoother signals tend to have a higher occurrence of small slopes between data points (gradual vs. abrupt transitions).

A scatter plot of the two features extracted from the training set is shown in Fig. 4. The linear discriminant analysis results using these two features gave 94% accuracy for in-shell nuts and 99% accuracy for kernels. However, the accuracy for this sample set can be improved slightly using a non-linear decision boundary (Eq. 2).

Classify as in-shell if:

$$\begin{aligned} &G(0.04) < 75 \\ &\text{OR} \\ &G(0.24) > 120 + G(0.04), \end{aligned} \tag{2}$$

where *G(0.04)* is the number of data points having a slope of 0.04 or less and *G(0.24)* is the number of data points having a slope of 0.24 or less. Using Eq. 2 as the decision boundary improves accuracy to 98% for in-shell nuts and 100% for kernels on the training set.

The signal processing algorithm and classification scheme defined by Eq. 2 was programmed onto the controller board for real time sorting. The signal was stored into on-board random access memory after triggering. After 250 points were collected, the signal processing and classification was performed. The post signal acquisition processing time was 4 ms. Since nuts were traveling at a speed of about 2 m/s upon impacting the plate, they would only travel 8 mm in the time it takes to process the signal. Results from the sorting experiments where nuts were fed at throughput rates of 10, 20, and 40 nuts/s are shown in Table 1.

Regression analysis confirmed a correlation between the feed rate of the nuts and the classification accuracy

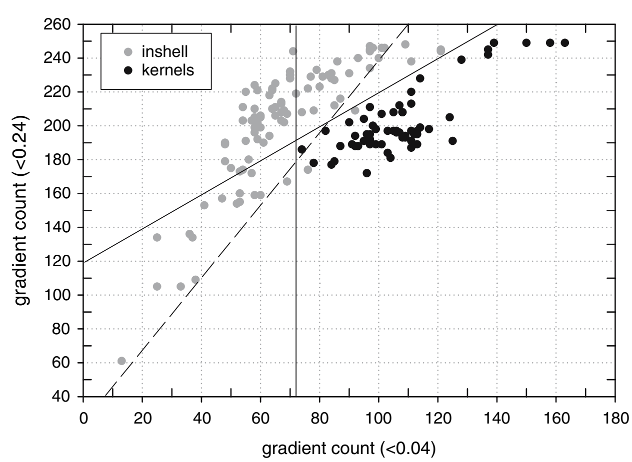

Fig. 4 Scatter plot of selected histogram features. The solid lines are the classification boundaries specified by Eq. 2. The dashed line is the decision boundary from the discriminant function. Data from the training set only

Table 1 Average sorting accuracies with standard deviations from ten sorting trials comprising 100 in-shell nuts mixed with 900 kernels

Nut type	Feed rate (nuts/s)		
	10	20	40
Kernel	95 ± 2%	95 ± 2%	89 ± 4%
In-shell	90 ± 3%	90 ± 4%	84 ± 7%

Table 2 Average classification accuracy ± standard deviations and classification plus physical diversion accuracy for nuts fed slowly, at an approximate rate of 1 every 3 s

Nut type	Classification accuracy	Classification + Physical diversion accuracy
Kernel	99 ± 1%	98 ± 2%
In-shell	96 ± 1%	91 ± 1%

(R^2 = 0.94 for kernels and 0.91 for in-shell nuts). The cause of this correlation is presumably close packing of the samples so that more than just the intended sample may be diverted by a single activation of the air nozzle. Since the nozzle is activated upon detection of an in-shell nut, the amount of error to be expected is dependant on the frequency of occurrence of an in-shell nut in the kernel stream. Here, the validation sample set comprised 10% in-shell nuts, which is an artificially high number. Typically, this is expected to be less than 1% and thus the error rate would be reduced. Clearly, when processing a stream of pistachio kernels with high in-shell content, reducing the throughput rate would be recommended for best results.

Table 2 shows the observed classification accuracies for very low throughput rates, which represents the accuracy of the algorithm. Also shown is the diversion accuracy. The classification accuracy and physical diversion accuracy for kernels were 99 and 98%, respectively. While these two mean values are not significantly different, it indicates that about 1% of kernels bounce sideways upon impacting the plate and are diverted to the in-shell stream, even though the air valve is not activated. Also shown in Table 2, it appears that approximately 5% of the in-shell nuts are not properly diverted by the air valve. This type of error is typical of most sorting machines. About half of the misclassified in-shell nuts in this study were observed to either have thin, soft shells, or small shells not covering the entire kernel. Hence the nut may have been oriented so that only the kernel portion impacted the plate.

Small in-shell nuts are currently sorted from the kernel stream using commercially available dual-band NIR sorters. These have been shown [1] to have better than 99% accuracy if equipped with the proper optics. However, these devices cost in the neighborhood of $50,000 per channel. The cost of the parts for the system described here was approximately $2,000 per channel, and the accuracy of the existing technology can be matched by performing a second sorting pass with the new system. Finally, in certain cases the new system is expected to detect heavily stained in-shell nuts that are fooled by existing technology which rely on color for detection.

Conclusion

A system has been developed to separate in-shell pistachio nuts from kernel processing streams based on the vibration induced on a plate from an impacting nut. The system was tested at throughput rates of 0.33, 10, 20, and 40 nuts per second. Sorting accuracies for in-shell nuts ranged from 96 to 84% with a strong correlation between accuracy and rates. Sorting accuracies for kernels were 99% for the lowest throughput rate of one nut every 3 s, 95% at 10 and 20 nuts/s, and 89% at 40 nuts/s. Cost for all parts in the system was approximately $2,000. The low cost and ability of the system to detect heavily stained nuts that are often fooled by color or dual band NIR sorters suggest this system may be a useful addition to existing equipment to help deliver kernel product free of in-shell nuts.

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